

ARMY RESEARCH LABORATORY



Scientific Visualization and User Interfaces in Composite Manufacturing Simulations

by Dale R. Shires, Robert S. Fink,
and Ram V. Mohan

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Abstract

The importance of graphical visualization and animation in manufacturing process simulations cannot be overstated. Indeed, without effective scientific visualization tools, process simulation resultant data cannot be properly interpreted and analyzed. Software and hardware can be combined to convert what used to be page after page of printed numerical results into animated, easy to see results which are quickly rendered on graphical displays. Results that used to take days of careful study to understand can now be comprehended in minutes. With this understanding in mind, we have set out to develop novel ways to both view and interface with our manufacturing process simulations. This report discusses our selection methodology for the hardware and software used for our visualization work and relates some of our experiences in constructing specialized graphical tools. Other areas of discussion include computer codes, free software tools to build interfaces, and tracking and graphical representation of simulated and actual manufacturing process data across networks.

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1 Introduction.

Simulation has become a valid and accepted practice in many scientific research areas. Maturing fields of study, whether it be weather forecasting or prediction of ballistic impact damage, are able to use simulations to accurately model the complex interaction of physical forces found therein. Accordingly, researchers and scientists are able to use these simulation models to study and analyze a wide variety of possible scenarios without the physical event ever taking place. The impact of this technology is far reaching. The U.S. Army is interested in simulation in many diverse areas. One area of particular interest to this group is the application of simulation technology to composite manufacturing.

1.1 Composites and the Army.

The use of composite materials in present and future combat systems is a necessity. With the changing national security posture, this is even more evident. The Army is focusing on Continental United States (CONUS)-based force projection. Emphasis is also being placed on the creation of "smart" structures. Composite materials, with their associated lightweight characteristics, will make combat systems lighter. This will make fast force projection possible. It has been demonstrated that composite materials can also take advantage of "in situ" sensors. Sensors incorporated into the composite part during its manufacture allow computer systems in the vehicle to monitor system integrity (health monitoring) and relay information quickly to operators. Composite parts are inherently superior materials for soldier protection from projectiles due to their energy-dispersing characteristics. Thick composites provide even better protection capabilities because they can be augmented with specialized protective devices such as embedded ceramic plates.

1.2 Virtual Manufacturing.

The challenge of using composite materials is in their manufacture. This process is inherently more involved than standard metals formation, for example. Today, composite parts manufactured with injection-molding techniques can be very time consuming and costly because the procedure is often trial-and-error. Usually, resins are injected into molds containing some sort of fiber preforms. These molds are then often autoclaved. Only when the entire process is completed do problems in the initial setup become evident.

Manufacturing simulation methods have been developed for composite materials to help reduce the number of trial-and-error iterations of the process. Most of these methods involve some sort of finite element approachs to modeling the flow of resin through the part mold and part preform. These methods appear to be quite promising at predicting possible problem areas.

However, simulations are only helpful when their results can be properly interpreted by researchers. Historically, these simulation codes are written by researchers who know their field of study very well. Unfortunately, they often have very limited computer science knowledge that would assist them in writing high-performance simulation models or generating output that could take advantage of graphics rendering capabilities in today's computer systems. Unfortunately, the results are often very detailed and accurate models with no way of effectively conveying simulation predictions. These simulations, in turn, are rarely used, or their results are simply ignored. We recognized this limitation early on in development of this simulation technology. Not only did we set out to develop new, fast, physically based composite manufacturing models, but we also wanted to develop them around a flexible and powerful scientific visualization framework. The successful integration of accurate models and scientific visualization tools is detailed in this paper. The tools and techniques used are detailed in two case studies.

2 Visualization Shortcomings in Simulations.

One of the most frustrating prospects of using most modeling and simulation packages is the amount of work that must be done to prepare the numerical input the program requires for execution. The idea of preparing this data by hand with a text editor seems ridiculous, but, often, this is the only avenue available. Computer-aided design (CAD) packages are available, like Pro/ENGINEER from Parametric Technology Corporation, to generate the geometric data involved with modeling structures. Even when these tools are available, unless a certain functionality is built in to the CAD package, the data from the CAD package must be reformatted and massaged to get it into a format for the particular code. It is up to the user to develop these computing routines to move data in one format to another.

Furthermore, there is no user interface associated with most research-driven, simulation programs. The entire simulation scenario must be described outside of the simulation context itself using applications that are not directly connected to the simulation run-time environment. The flat data files describing the simulation scenario are often generated and then passed on to the simulation program. One can easily see that an important component to the description stage, the ability to view the part or data being investigated, is missing from this methodology. The task of describing the simulation scenario without the ability to view the data makes the process much more difficult. For example, consider the task of identifying a certain corner node in a large, three-dimensional (3-D) finite element mesh based on simply the numerical data describing the list of nodes and their x , y , and z positions in space. With even moderately complex surfaces, the process becomes quite involved and time consuming. Most of these simulation programs lack these preprocessing mechanisms to help the user describe the modeling scenario in an easy way.

Data output from these simulation programs can easily be just as complicated

as, if not more so, the data input. Proper scientific visualization techniques applied to resultant data allow engineers to quickly determine those effects predicted by the simulation. There are several data visualization packages available today. What we are proposing, however, is the complete, integrated package where simulation scenarios can be detailed and interacted with quickly and easily and provide result visualization capabilities. Denying the user visual, interactive interfaces is rather austere in an age when computing resources can be used effectively in so many areas.

3 Developing Interfaces for Scientific Visualization.

Computer simulations can only influence manufacturing if they are actively used and continually enhanced. Since many of these simulations are cumbersome and hard to program, they are seldom used and are rarely augmented. Many are not used beyond their first version or two. To promote utility and understanding, scientific visualization can be used. In these situations, effective visualization puts results into layman's terms where individuals with an even cursory knowledge of the subject area are able to comprehend resultant data. Making data meaningful for everyone helps to promote use and ensure the longevity of the simulation effort, thus allowing the technology to mature.

3.1 Computing Hardware.

In government, academia, and industry, most scientific codes are developed in a UNIX environment. Resource sharing, faster processors, and more robust compilers are just a few of the reasons for this. Of additional importance to us was graphics-rendering capabilities. Silicon Graphics Incorporated (SGI) computers, with their robust compilers and fast 3-D graphics-rendering and manipulation capabilities, were the obvious choice. SGI is actively manufacturing and marketing more lower-priced computer systems. Accordingly, such machines should become even more prevalent in government and industry.

As the dividing line between personal computers (PCs) and workstations continues to blur, we have positioned ourselves to transfer these capabilities into the PC world as time permits. Faster processors on PCs are allowing for true multitasking and are providing faster graphical-rendering capabilities. Interfaces can be designed and implemented in several different environments, and the graphic-language tools described in the next sections (OpenGL and Open Inventor) have migrated to the PC-development arena.

3.2 Software Development.

3.2.1 X11/Motif.

Most user interfaces in the UNIX environment are constructed from the X11/Motif programming toolkit [1]. The X window system is an industry-standard system that allows programmers to develop point-and-click graphical interfaces that can be migrated across computer platforms [2]. X is based on a client-server model. The X server handles all input and output devices. A client is an application that uses the devices provided by the server. X supports many network protocols allowing the server and client to run on separate computers. A client may run on a local server. For example, an SGI workstation may run several clients, such as graphical clocks, incoming mail notifiers, etc., which use the X server in the workstation itself. This network capability also allows for more complex scenarios. For example, an expensive CAD package may be shared by several users at once. The CAD package can be executing on one central computer with users at separate terminals (X servers), each using the application with individualized graphics.

Programming in X alone is a rather mundane and difficult task. The Motif library is built on top of the X11 code and provides a framework to implement user interface components, such as scroll bars, menus, and buttons. Most of the user interactions with our simulation codes are done through X11/Motif interface “widgets.”

3.2.2 OpenGL/Open Inventor.

The graphics hardware has to have some avenue by which it is controlled. OpenGL (graphics language) provides an interface to the graphics hardware. OpenGL is also based on a client-server model. The code running that issues OpenGL commands is known as the client. The computer that performs the drawing is known as the server. If there is only one computer performing both tasks, then it is both the client and the server [3]. OpenGL is hardware independent, but it is closely tied to the operating system and the graphics hardware.

Just as Motif seeks to simplify programming in X, so to does Open Inventor seek to simplify programming in OpenGL. Open Inventor is an object-oriented, 3-D toolkit [4]. It is based on OpenGL and provides a library of graphical objects that can easily be rendered or manipulated.

Inventor is designed to create 3-D objects. All of the information about the objects, such as their color, positions, etc., is stored in a data structure known as a scene database. This scene database resembles a tree structure. When the scene database (or scene graph) is rendered, it is traversed top down and left to right. Nodes down and to the right inherit properties from nodes to the left and above. Nodes, such as separator nodes, are available to limit this inheritance. Figure 1 illustrates an example scene graph.* This figure illustrates a simple robot object in Open Inventor.

*Example taken from Wernecke.

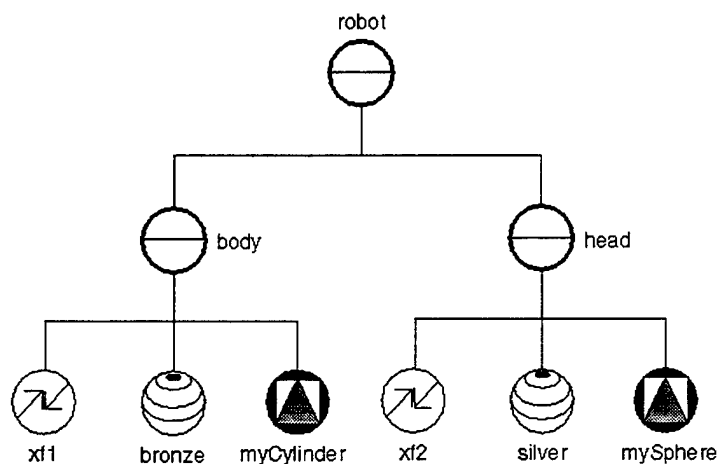


Figure 1: A Simple Example Scene Graph.

It consists of nine nodes, each describing the geometry that is to be rendered on the computer monitor. The first node encountered during the traversal of the graph is the “robot” node. This node is a separator node that serves to group objects and limit the inheritance described earlier. From the scene graph we can see that a robot is made up of a body and a head. The second node encountered is the “body” node. The third, fourth, and fifth nodes encountered are the “xf1,” “bronze,” and “myCylinder” nodes, respectively. The first of these nodes is a transformation node. It sets the location for the next rendering action. The bronze node is a material node. This node is used to set various rendering characteristics, such as color and transparency. The myCylinder node is a shape node. Shape nodes can be such things as cylinders, cones, or spheres. Each of these nodes has its own description fields. A sphere has a radius field. Cylinders have fields to describe the radius and height of the part. By the time the cylinder is rendered, its position is set and its material characteristics have been set. Traversal through the “head” tree occurs in the same manner. As one can see, the design is logical and can be presented in a clear fashion. Construction of these scene graphs in the computer is equally straightforward.

Open Inventor solves the problem of representing complex shapes quickly and easily. However, standard interface tools are still required to allow users to interact with the scene graph. SGI has made this process easier by providing a framework where examiner viewers, those used to view 3-D geometries, are tied to X11/Motif application development environments. Standard windows are provided for rendering 3-D Open Inventor scene graphs. These windows can be incorporated into X11/Motif interfaces that provide menus, buttons, and other widgets essential for user interaction. The following case studies provide more detailed examples.

4 Case Studies.

4.1 Virtual Composite Manufacturing.

The main focus of virtual composite manufacturing and virtual process modeling is to develop physically accurate process models to simulate the Liquid Composites Molding (LCM) processes such as Resin Transfer Molding (RTM). The properties of stiffness and high strength to weight ratio makes composites attractive for many applications. For example, some of the latest aircraft designs must cope with enormous loads. Constructing safe components from lightweight aluminum would render the structure too large or too heavy. Substituting composites for metal makes the design practical.

One of the most promising techniques in composite manufacturing is to use "pre-forms" that are pressed beds of fiber arranged in the shape of the final structure. The preform is placed inside a mold and then resin is injected under pressure. This technique is referred to as resin transfer molding (RTM). With proper design, RTM can mass-produce net-shape, high-performance parts with low void fraction. Furthermore, the RTM process allows for inserts such as titanium rods for load bearing portions or placement of in situ sensors within a part.

The RTM process requires several parameters (e.g., placement of resin injection and vent locations) to be predetermined for mold design. Often, however, the RTM process is a trial-and-error endeavor. Poor decisions during the mold design stage will often produce parts where air pockets form, causing incomplete wetting of the fiber preform; or, resin cure can start to occur before the entire mold is filled. Both of these situations render the final part unusable, and the mold must be retooled for the next trial.

Simulation technology offers an excellent avenue to increase the integration of manufacturing influences into product development. In fact, experimenting in a virtual world has a direct impact in lowering product development costs and improving the acquisition cycle. Optimizing process parameters through parametric studies in a virtual environment allows design engineers to understand the manufacturing processes involved during RTM and significantly lowers the amount of retooling that must be done. This lowers the final cost of the part and also reduces the time to field new combat systems. Because RTM and composites in general are being utilized more and more in industry, this technology is also a dual-use one. Whether it be construction materials, airframe components, etc., manufacturing simulations benefit all those involved with composite manufacturing.

As an example of costly trial and error production, a 10-ft keel beam section from the Army's Comanche helicopter program took the manufacturer approximately five trials to get a part that was free from defects. Each retooling cost approximately one million dollars and took about six months to complete. The impact on cost and time to field the Comanche helicopter is obvious. Process simulations offer a way to reduce

these trials.

Based on these objectives, the U.S. Army Research Laboratory (ARL), along with the Mechanical Engineering department at University of Minnesota, has developed a pure finite element methodology for RTM flow simulations [5, 6, 7]. It is based on the transient mass balance equation for the resin mass in conjunction with an implicit filling technique which provides solutions for both the pressure field as well as the resin front progression. Compared to the explicit finite element-control volume (FE-CV) methodologies used in other approaches, the new methodology developed is faster and is more physically accurate.

Along with getting the mathematics of the simulation correct, we were also very concerned with making a truly useful tool. In particular, we wanted a tool that provided:

- easy and quick interaction,
- limited off-line data manipulation,
- 3-D graphics rendering, and
- postprocessing capabilities.

By using the SGI computer system with custom-built interfaces from X11/Motif and Open Inventor, we have met these goals.

Easy interaction is provided by the point-and-click interface provided by the X11/Motif environment. While programming in these systems is not trivial, it is also not impossible given a few good examples and a robust compiler. Users can quickly set what action they would like to perform. For example, it is very easy to place boundary conditions like injector locations. These items can be graphically represented by adding objects representing the injectors to the global scene graph being rendered. Quick, context-oriented help may also be programmed into the interface that speeds the familiarization process as well. The SGI hardware provides the smooth-flowing, 3-D graphics that make data interpretation quite easy.

Limited off-line data manipulation was also a high priority. By this, we mean spending little time "massaging" data files into some strictly formatted conventions. No one wants to spend time putting together large data files describing modeling geometries and scenarios. This system incorporates a data parsing system that can quickly read in NASTRAN files from mesh generation software. The geometry is formatted into an Open Inventor scene graph while it is being read, and the graphic is then rendered by the SGI. Any number of parsers can easily be constructed to allow the interface to read different data file formats [8].

Post processing passes are also easily incorporated. Most of these are simply passes over the scene graph generated from the simulation results. We have developed and incorporated passes that animate predicted resin flow from the simulation. We also have passes that allow users to "band" the flow fronts based on time intervals.

Figure 2 shows the finite element mesh created for a sample Army composite part. This mesh was generated from Pro/ENGINEER and saved as a NASTRAN file. It is this finite element file that serves as the basis for performing our simulation code. The engineer is able to use our interface to quickly read in this NASTRAN file and render it. The engineer is then able to set certain boundary conditions and start the process simulation.

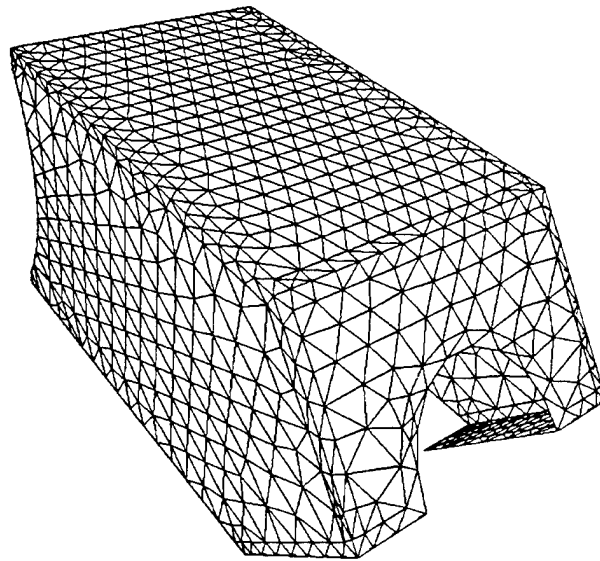


Figure 2: A Representative Finite Element Mesh.

Figure 3 shows the composite part geometry in the user interface after the simulation code has completed. The injector locations set by the engineer are shown as simple spheres. These injector locations are specified by simply selecting the “place injector” option and then clicking near the node where the injector is to be placed. On the computer screen, the part is shaded in a full-color, rainbow-like fashion based on the predicted resin flow through the part mold. For purposes of publication, a gray-scale representation is given in the figure. While not as ideal as a color rendition, this gray-scale figure still shows the resin race-tracking effects on the part edges. Race-tracking is a well-known phenomena, where resin moves faster in sharp corner areas. Areas near the injectors are obviously filled first, with the darker areas near the bottom of the part being filled last. Boundary conditions can be added, deleted, or even edited. For example, injector boundary conditions can be easily removed once placed. Also, they contain certain fields that can be edited to influence the process simulations. Some of these include pressure data, time to activate the injector, and time to shut off the injector.

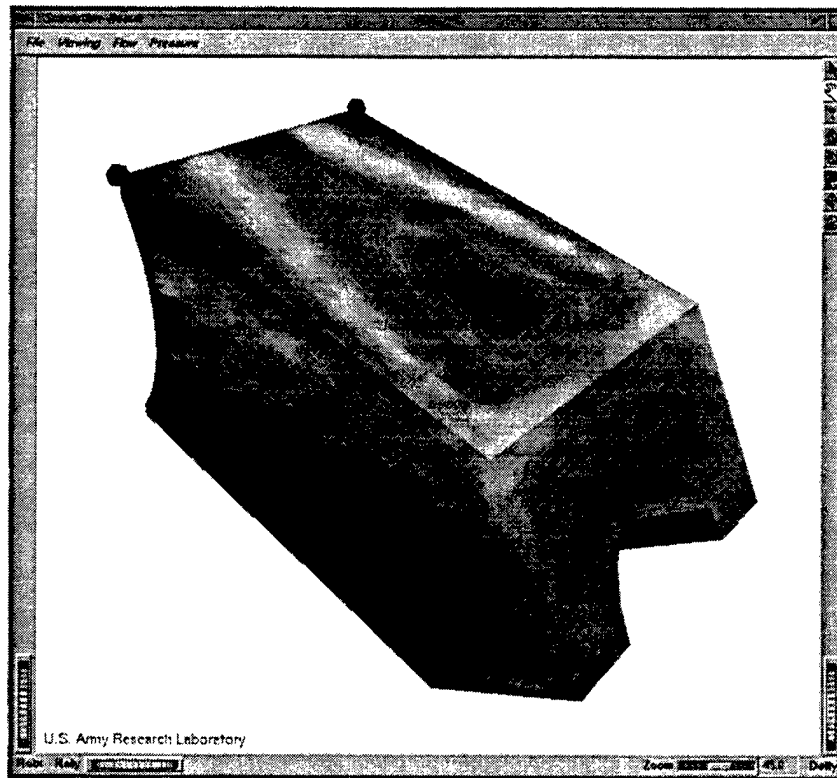


Figure 3: Virtual RTM Flow Simulation Result.

4.2 Embedded Sensors.

Composites are attractive for many reasons. Yet another is the ability to incorporate in situ sensors into a composite part. These sensors can be used for many purposes. One use is in the actual manufacturing process [9]. Sensors placed in the fiber preform can be monitored during the resin-filling stage to monitor the resin flow front. As resin hits the sensors, they can in turn relay this information to a controlling device. This presents a framework for intelligent processing. By using a well-defined control strategy, an automated processor controlling the RTM process can use sensor information to help guide the part formation process. For example, if resin is not flowing into a region at a fast enough rate, the controller could start multiple-point injections to speed the process.

Another use for sensors is apparent in the fabricated part. These sensors can be used to detect damage in a part. They can also be used for condition-based maintenance. This is a maintenance strategy, where the part actually informs mechanics and engineers of potential areas that need repair. The applications are seemingly endless, from aircraft, to ships, to land vehicles. Recognizing the potential for such devices, ARL developed the SMARTWeave system [10]. As a very rudimentary description, this system entails weaving conductive fiber tows through composite preforms. These

tows are then multiplexed with low-voltage electrical current being applied to parallel tows and sensing being performed on the tows running perpendicular. Basically, a grid pattern is formed with intersection points forming sensor locations. For example, a 7×7 grid would yield 49 sensor points. Figure 4 illustrates such a SMARTWeave grid.

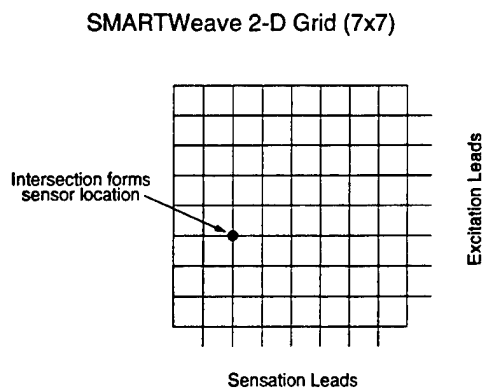


Figure 4: A SMARTWeave 7×7 Sensor Grid.

Based on predetermined thresholds, voltages at the sensor points were indicative of whether or not resin had reached the sensor. The user was presented a graphical, two-dimensional (2-D) representation of the preform that was colored based on flow progression through the mold. This visualization tool was constrained, however, to 2-D cases like those depicted in Figure 4. Therefore, only simple, flat panel experiments could be viewed using these techniques.

Customized user interfaces using the software and hardware described earlier provided an ideal solution to this limitation. This presented some interesting difficulties to overcome, however. The SMARTWeave system is designed to be somewhat inexpensive. This facilitates taking the machine "on the road" to do experiments and gather data quickly. In order to view the 3-D experiments, a method to get the data from the PC to the user interface had to be developed.

We decided on writing some routines that would allow us to communicate over Transmission Control Protocol/Internet Protocol (TCP/IP) network channels. Most workstations in the SGI family are network-ready. Code that allows users to specify a TCP/IP socket that will act as a listener was written. The PC running the LabVIEW software was also fitted with a network card. The LabView software on the PC has software that supports TCP/IP calls. This allows the PC user to input the internet number of the SGI workstation and the port to which it should connect. The PC then collects the SMARTWeave data and sends bursts of data over the network to the SGI workstation. This system has two advantages: it does not require specialized connectors to interface the two systems, and it allows for distributed data collection and visualization.

Figure 5 shows the user interface for the SMARTWeave monitoring system. This

is a sample thin composite structure that is being manufactured using RTM. Users are allowed to set process parameters in the "Network" and "Monitor" menus. Sensor positions are represented by small diamond shapes. The dark diamonds are sensors that have not detected resin. Lighter diamonds are those areas where resin flow has occurred. The injection is accordingly at the center of the light-colored diamonds in the upper corner of the part. The user is free to spin and rotate the part even as data collection continues to occur. We visualize this system as being an integral component to a controlled manufacturing process based on sensor data.

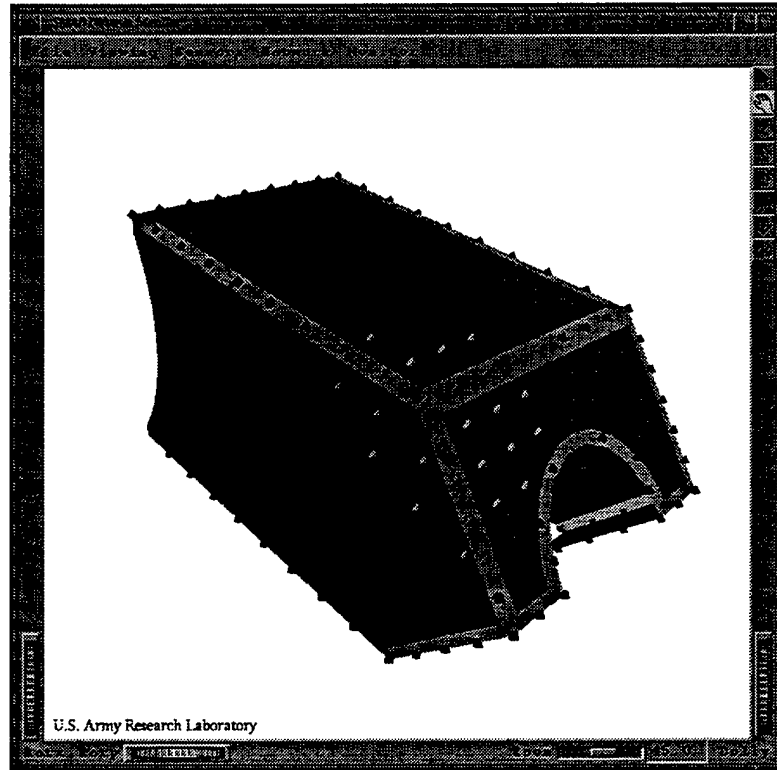


Figure 5: 3-D SMARTWeave Monitoring.

5 Future Directions.

Of current research interest to our group is manufacturing simulations related to thick composites [11, 12]. Many land combat vehicles will be using thick composite sections in their hulls. Some of these plates will have a thickness exceeding 1 in. Thin composite manufacturing simulations involve 2-D meshes that show no thickness. On the other hand, 3-D flow simulations have meshes that have thickness. The problem is in how to visualize the resin flow front that is occurring inside the part. We are currently investigating tools constructed in Open Inventor that will let us visualize the flow front through a cross section of the thick composite section.

Sensor visualization is also being augmented with a resin-flow-front reconstruction algorithm [13]. Previously, the capability existed only to visualize sensor activity. We have since added the capability to reconstruct the resin flow front based on time and sensor data. The result is a sophisticated curve-fitting approach to determine the resin flow front at discrete time intervals. This technology is currently being incorporated into the user interface to allow for an even more robust visualization capability. The user can see in almost real time the flow progression in closed-mold RTM injections. This work is described in an upcoming technical report.

Furthermore, we are also actively pursuing technology in the internet domain. Even though SGI workstations are becoming more common, it is somewhat constraining to fully rely on this architecture alone. We are striving to make this technology applicable from any networked computing platform. To this end, internet technologies such as Java and the Virtual Reality Modeling Language (VRML) are particularly desirable. These facilities add a level of abstraction to the modeling environment. Any networked computer with a browser capable of interpreting these languages will be able to render manufacturing simulation results. These techniques also present the ability to do interactive modeling from remote regions. Thus, it would be possible for design engineers on the west coast of the United States to make interactive changes to models running on the east coast. When the simulations complete, results can be visualized through the Java/VRML interface and will require no specialized hardware.

6 Conclusion.

A great deal of time and energy goes into making process simulations as physically accurate as possible. This is the basis for any simulation. But this is only one of three requirements that must be met to make simulations truly worth the effort. They must also be easy to use. Without this characteristic, simulations will be considered too complicated and time consuming; hence, they will never be used and will never mature. Finally, their results must be easy to interpret. Surely, each one of these is just as important as the other.

This paper has presented two case studies involving technologies that have dramatically improved their utility by considering scientific visualization an important part of their final product. In both cases, these were technical problems addressed by interdisciplinary teams involving engineers, computer scientists, and physicists. Each of the three characteristics listed in the previous paragraph were given equal weight in these technology developments. While designing scientific visualization capabilities is not trivial, the effort spent in this endeavor is quite worthwhile.

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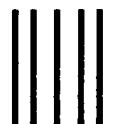
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